Paper presented in the VI Globelics Conference, September 22-24 2008, Mexico City

Globelics

Patterns and Processes of Contemporary Technology Fusion: the Case of Intelligent Robots

Lee, Kong-rae[1]

Summary

This paper aims to understand the patterns and processes of contemporary technology fusion. It attempts to argue that the mechanisms of technology fusion in upstream research activities typically begin as the researcher with a cognitive map as technology interacts with another researcher holding different cognitive maps. Their interaction evolves into a collective learning that causes the generation of a new knowledge. The collective knowledge also creates a new technology after it integrates into or absorbs a codified and tacit knowledge created by a third researcher with other knowledge. The creation of collective knowledge requires purposive effort as Martin Bell argued. Under active social interaction of many researchers, the diversity of applications for a given technology is quite large so that the possibility of technology fusion to create new functions and products becomes available.

In the case investigation of intelligent robots, technology fusion appears to be quite distinctive wherein core technologies such as digital data treatment, control or adjustment, and manipulation lead the integration of various technologies to produce such. The literature analysis using abstracts of 624 papers on intelligent robots provided such key words as humanoid, control, service robots, sensors, systems, vision, manipulators, learning, micro/mobile, teleoperation, software, etc. It was found that vast areas of knowledge including humanities have been integrated into research on intelligent robots. It also implies that diverse knowledge is fused or integrated in the process of basic research before the commercial development of intelligent robots.

Keywords: technology fusion, technological convergence, technology integration, Martin Bell, intelligent robots

[1] Science & Technology Policy Institute (STEPI) 26th Fl., Speciality Construction Center, Shindaebang-dong, 395-70, Dongjak-ku, Seoul, 156-714, South Korea (leekr@stepi.re.kr)

1. Introduction

Contemporary technological innovations in Asia have been featured as having a variety of characteristics, from simple learning for imitation to complex learning for more advanced innovations. Technology fusion is a type of innovation that generally took place in Japan in the 1980s that bridged her electronic technology and mechanical technology. Many technologically advanced countries including Korea have been now entering into the creation of frontier technologies which obviously requires fusion of diverse technologies. Innovation paradigms dominated by information and telecommunication technology have been moving into a technology fusion stage in which ICT technology integrates into many areas of manufacturing technology creating new products. Therefore, it is important for Korea and other advanced countries to understand the dynamics of contemporary technology fusion.

How do we understand technology fusion, which is likely to be a distinctive nature of contemporary innovations? It requires adoption of the concept of "a learning process or learning system" put forward by Bell (1984). In other words, it requires purposive collective efforts in activities such as intentional search, gaining and providing feedbacks, learning-by-hiring, learning-by-cooperating, etc. The terminology "technological capability" mentioned by Bell and Pavitt (1995) can be also applied to the understanding of technology fusion. Successful fusion of different technologies can be based upon inter-firm linkage capability and coordination capability or integrative capability (Fujimoto, 2007). It also requires a capability to conduct interdisciplinary research and development, which inevitably goes with trial and error, inter-firm linkages, networks, and a complex mutual learning mechanism.

In the downstream area of research activities, the nature of technology fusion in new innovations has been increasingly acknowledged in science and the technology community. Technology fusion is also widely perceived as a way to generate a synergy effect in research activities. It has been often believed that technology fusion plays a critical role in the innovation of next- generation products to gain competitive advantage at the level of nations, regions, and firms. The success achieved by Japanese companies in world markets was often attributed to their ability to integrate different technologies and systems. Such an approach is becoming increasingly crucial in the context of structural change in the world economy (OECD, 1993).

This paper aims to understand the process and patterns of contemporary technology fusion. It tries to argue that technology fusion typically begins as the researcher with a cognitive map on a technology interacts with another researcher holding different cognitive maps especially in the upstream part of research processes.

Their interaction evolves into a collective learning that causes to generate a new knowledge. The collective knowledge also creates a new technology after it integrates into or absorbs a codified and tacit knowledge made by a third party with other knowledge. This paper investigates intelligent robots in order to apply the concept of patterns and processes of technology fusion, and carries out the literature analysis using abstracts of 624 papers on intelligent robots for obtaining implications on a qualitative feature of knowledge fusion.

2. Definition and Patterns of Technology Fusion

2.1 Definition of Technology Fusion

A similar expression of technology fusion can be found as "technological convergence" in the article "Technological Change in the Machine Tool Industry, 1840-1910" made by Rosenberg (1963, 1982). At the end of the 19th century, all machines confronted a similar collection of technological problems dealing with such matters as power transmission, control devices, feed mechanisms, friction reduction, and a broad array of problems connected with the properties of metals. These problems became common to the production of a wide range of commodities. These were apparently unrelated from the point of view of the nature of the final product. The uses, however, of the final product were very closely related on a technological basis. Rosenberg called this phenomenon as "technological convergence" and argued that the intensive degree of specialization which developed in the second half of the 19th century owed its existence to a combination of this technological convergence.

Rosenberg found that very closely related technological problems were solved and shared among different types of machine manufacturers. Technological convergence has prevailed in contemporary innovations too, which center on information and telecommunication technology. It has evolved up to the point that different technologies are deeply integrated and even chemically mixed, resulting in completely new types of technologies and products. For instance, a newly developed music receiver called an MP3 is a product of fusion of many different technologies associated with Walkmans, records, digital music, compact disc players, the Internet, etc. New products developed through technology fusion increasingly appear in the modern innovation scene. This phenomenon has been often called 'technology fusion' as it may be too weak to express it as technological convergence.

The term 'technological fusion' was in Kodama's papers (1986, 1991, 1994). He argued that there are two fundamental types of innovation: one is the technological breakthrough and the other is a technology fusion. According to Kodama, breakthrough innovations are associated with strong leadership in a particular technology, and technology fusion can be possible through concerted efforts by several different industries. He put particular emphasis on the latter because it contributes not only to the rapid growth of companies that make technology fusion possible, but also to the gradual growth of all the companies in many industries. He empirically observed a phenomenon of technology fusion that occurred first between machinery industries and electronic industries in 1970, and later among variety of industries including chemicals, foods, and pharmaceutical industries in 1974 and 1975 (Kong-rae Lee and Jung-tae Hwang, 2005).

Kodama's paper mainly featured new trends in Japanese innovations aside from the phenomenon of technology fusion. However, he did not clearly define technology fusion. What he mentioned was that technology fusion can be made possible through concerted efforts by several different industries. A concrete definition on technology fusion has to be made before identifying its patterns and processes. Technology fusion is defined here as a horizontal integration of diverse technologies.[2] Horizontal integration means an absorption of diverse fields of technologies for the purpose of creating new functions and products, which often broadens the scope of their technological specialization that can interact with partner companies.[3]

Table 1: Comparison of Characteristics between Fusion and Combination

	Technology fusion	Technology combination
Overall technology feature	Emerging technology	Improving technology
Character of technical	Change after fusion	Maintain after
Complexity of products	Reduced or increased	Increased
Nature of innovations	Creative and radical	Improvement and
Project characteristics	Interdisciplinary teams	Well coordination
Character of product markets	New market creation	Expand existing markets

Source: Kong-Rae Lee and Jung-Tae Hwang (2005), *A Study on Innovation System with Multi-technology Fusion*, pp. 16-18, Seoul: STEPI Policy Study 2005-17.

Technology fusion may be better understood by comparing its characteristics with technology combination in many aspects. As shown in Table 1, overall technology feature of fusion is likely to be emerging technologies while technology combination accounts for improving technology. Character of technical elements may be changed after fusion, whereas it remains the same after combination. On the other hand,

2 Ther term "horizontal integration" in this paper is not same as that explained by Teece (1976) who indicated the term as an organizational integration over value chains.

3 Iansiti (1998) stated that technology integration is made up of the set of problem-solving activities that are performed to match a new element of technical knowledge to the complex architecture of established competences.

complexity of products is likely to be reduced or increased after fusion occurs because some components may be chemically melted down into some other technologies, while it is vice versa for technology combination since original components remain the same as before. Product complexity can arise from many sources. Technology fusion may simplify the production process and design for one generation of products, but lead to more complexity/lock in to the next generation of products.[4] Similarly, technology fusion reveals a creative or radical change in the final product, as in the nature of innovations, but technology combination may merely show improvements and upgrades.

Figure 1: Differences between Technology Fusion and Technology Combination

Technology fusion requires knowledge collaboration of several different industries, which also indicate the inclusion of different people, technologies, and firms. In other words, it needs interdisciplinary research teams composed of many different people with technological knowledge wherein they interact together creating new ideas and knowledge. However, technology combination may simply need a proper coordination of different component technologies, which does not need complex knowledge activities.

On the product market side, technology fusion may generate more new markets for new products and functions (Lim, Woo-Suk, 2004) than technology combination does. The difference between technology fusion and technology combination can also be depicted by making simple shapes as Figure 1. The former reveals a characteristic that two different technologies (A and B) create a new technology or a thing (C), while the latter maintain their original properties (A and B) after combining, like AB in the illustration.

2.2 Patterns of Technology Fusion

Theoretically, the result of technology fusion may appear in two types as shown in Figure 2. One is a convergence type in which a technology (A) which may be critical in generating certain functions of products or services, tends to converge into many

[4] With technology combination, complexity is often determined by the nature/simplicity of the interfaces between components/ and also the prior knowledge of the firm. What has been done many times by one firm appears very simple to it, but might be extremely complex for another firm with little experience.

different technologies (T_1, T_2, T_3). The other type is a fractal type in which two different technologies (A and B or D and E) fuse and create a completely different type of technology (C, F, and G). The MP3 case, for example, can trace its roots back to the 1970s, when electronic technology and conventional mechanical technology married, creating numerical controllers (NCs). The NC technology is a product of fractal-type technology fusions between electronic technology and conventional mechanical technology. It has been adapted and applied to various machine tools performing new functions. This fusion at a later stage can be considered a type of convergence of technology fusion.

Today, information, communication and telecommunication technologies (ICT) show similar patterns of technology fusion as the NC in the 1970s. Code division multiple access (CDMA) system for mobile communication is an example. It is a new mobile telecommunication system that enables many-to-many mobile communications at a single time. It was created by the fusion of many technological components such as digitals, air interface, transceiver system, control system, location register, switching, telephone network, handsets, etc. (Lee, Kong-rae, 1999). Technology fusions that arose with the innovation of the CDMA system might be the mixture of fractal types and convergence types. Mobile communication technology has nowadays been evolving into various applications through fusion for a customized convergence, in which seamless and ubiquitous communication can be made possible through an all-IP based network (Seok-Ji, Park, 2004).

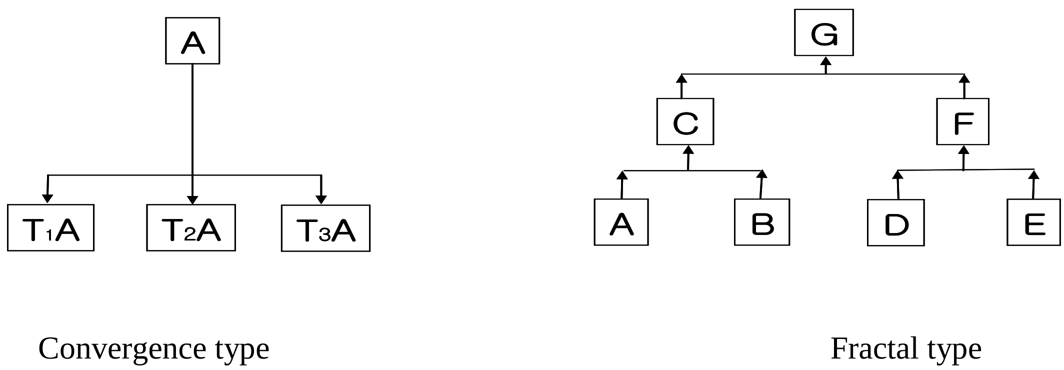
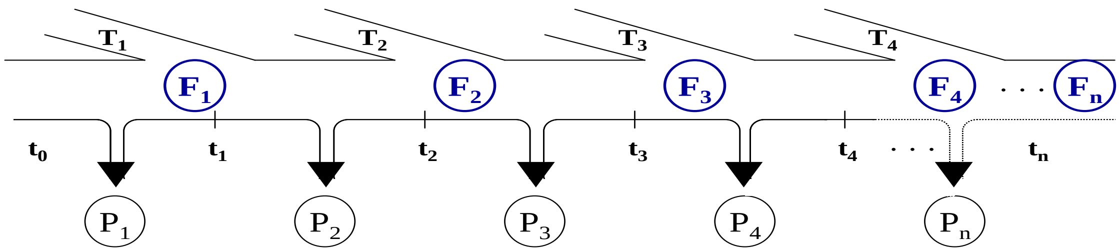


Figure 2: Patterns of Technology Fusion

3. Processes of Technology Fusion

It is theoretically argued that technology fusion has a property of life cycle like any other product. It begins as researchers start socialization in research work to learn a different technological knowledge. Then, an innovation emerges as the researchers generate a new knowledge that becomes a source of new functions or new products. Creative knowledge becomes a routine knowledge as the researchers stop learning to add new things, moving to a stabilization stage that finishes a life cycle of technology fusion.

The process of technology fusion can be simply depicted as in the Figure 3. As time goes, research and development teams may learn new technological knowledge (T_1) at time period of $\mathbf{t}_1$, and create a new function ($\mathbf{F}_1$) and new product ($\mathbf{P}_1$) through the fusion of different technologies. It is an innovation at time period of $\mathbf{t}_1$, which is an incremental or a radical. At the time $\mathbf{t}_2$, researchers again learn new knowledge (T_2) as innovated knowledge at time $\mathbf{t}_1$ comes to obsolescence. The result of this is that they create new functions and new products (F_2 and P_2) through technology fusion like that of the time $\mathbf{t}_1$. This process continuously takes place by the time $\mathbf{t}_n$ unless they stop. It may be, however, much more complex in reality than this simplified process.



t_1, · · · · · · ·· ·· · t_n : time
T_1, T_2, · · · · · · T_n : technological elements
F_1, F_2, · · · · · · F_n : functions of products
P_1, P_2, · · · · · · P_n : new products

Figure 3: A Process of Technology Fusion

Modern innovations have an innate nature as being products of technology fusion because various professionals play concerted roles in creating new technologies. The researcher does observation, analogy, discernment, and behavior during the process of creating technology T_1 or knowledge A. The mechanism of technology fusion begins as the researcher with a cognitive map on one technology (i.e., T_1 of person A), interacts with another researcher holding a different cognitive map (T_2 of person B) as depicted in Figure 4. Their interaction evolves into a collective learning that causes the generation of a new knowledge (D). The collective knowledge also creates a new technology (T_4) after it integrates into or absorbs a codified and tacit knowledge (C) made by the third researcher with other knowledge (C). This process involves socialization, externalization, and combination and internalization of knowledge, which was explained by Nonaka (1994).

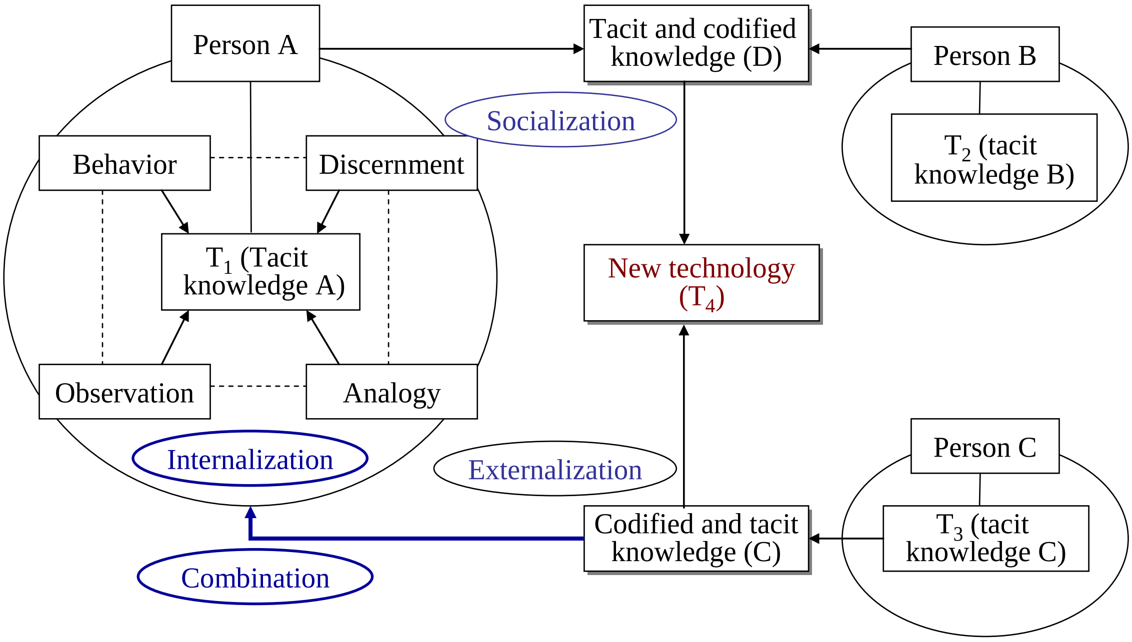


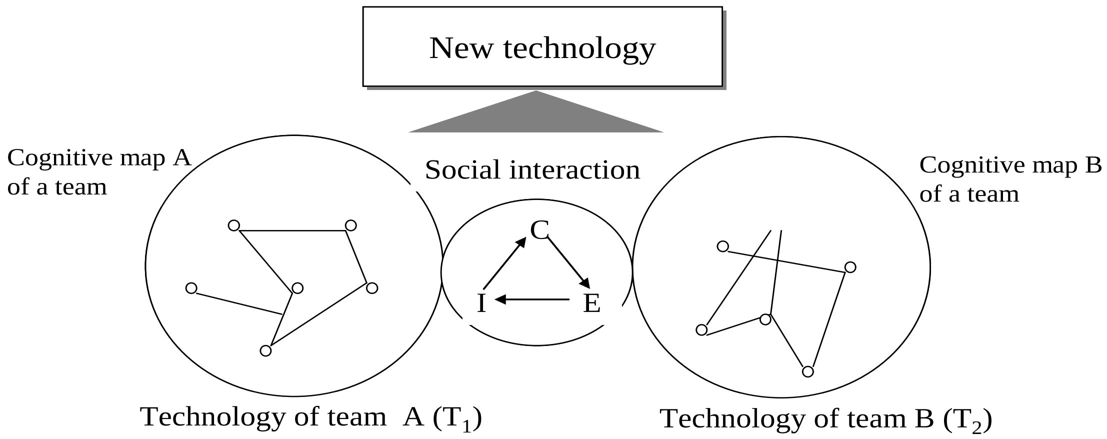
Figure 4: Learning Mechanisms for Technology Fusion

New technology created in the process of technology fusion is embodied in an organizational cognitive map that is the result of collective learning activities. Collective learning is distinctive feature of contemporary technology fusion, which includes knowledge activities such as acquisition, assimilation, integration, and creation of technologies for a new product at the organizational level. Social interaction is a bridge for technology fusion between as diverse persons with different cognitive maps are involved, as shown in Figure 5.

Through social interaction and learning, people inside the organization communicate, evaluate, and integrate technical information and provide knowledge to each other, ultimately creating a new technology. Under active learning and social interaction, the diversity of application areas for a given technology is quite large so much so that the possibility of technology fusion to create new functions and products is made available. That is why large R&D organizations are able to achieve multi-product diversification through active integration of diverse technologies. Large size

R&D organizations may have a capability to pursue technology fusion based on their large scope of knowledge (Teece, 1976). Whereas, small and medium sized firms may have limited capability to do such.

In this aspect, managing the process of technology fusion is primarily a function of the creation of conditions under which learning opportunities emerge and are exploited (Tidd, Bessant, and Pavitt, 2001). It implies that making the learning organization work, no matter what criticisms the public sector or the private sector might have, is crucial for successful technology fusion. It also implies that to understand technology fusion at the organizational level, it is important to identify its patterns and processes. Obviously, further studies are required in this area.



Notes: C (Communication), E (Evaluation), I (Integration)

Figure 5: Collective Learning for Technology Fusion

4. Measurement of Technology Fusion

Can it be possible to quantitatively measure the degree of technology fusion? Defining technology fusion as a horizontal integration of different technologies, one way to measure it is to identify integration patterns of technologies. It may be hardly possible to quantitatively measure technology fusion if it is of the fractal type. However, it may be possible to measure a convergence-type technology fusion, since original components of technologies remain after a fusion takes place. Assuming we measure the convergence-type, the intensity of technology fusion can be theoretically expressed as an exponential function of a number of different technologies as follows.

$$S = \frac{1}{e^{\alpha X}} \qquad (1)$$

$$\ln S = e^{-\alpha X} \qquad (2)$$

Where S indicates intensity of integration between technologies, X indicates the numbers of different technologies; α is a coefficient indicating a pattern of their integration. The function explains that intensity of technology integration exponentially decreases as the number of integrated technologies increases. The range of technology fusion increases as the number of integrated technologies increases. Patent data have often been used to empirically measure the intensity of technology fusion (Hwang, Jung-Tae, 2005; Hwang, Jung-Tae and Kim, Byung-Keun, 2006 and Kumaresan, 2001). This method is useful to estimate the intensity and range of technology integration which also reveals the pattern of technology fusion. Comparing different patterns of technology fusion certainly provides insight into R&D planning and policy for making effective technology fusion.

Another method to measure the intensity of technology fusion is to calculate cumulative proximity (CP) between different technologies i and j using patents class citations. It assumes that frequent co-occurrences of i and j technologies in patents indicate a close cumulative proximity and also a strong relation of technology fusion between these two technologies. The CP function can be expressed as equation (3) and equation (4).

$$CP_{ij} = \sum_{1}^{i,j} \frac{C_{ij}}{C_i \cdot C_j} \qquad (3)$$

$$= \sum_{1}^{i,j} \frac{C_{ij}/N}{C_i/N \cdot C_j/N} = \sum_{1}^{i,j} \sqrt{\frac{(C_{ij}/N)^2}{(C_i/N)\cdot(C_j/N)}}$$

$$= \sum_{1}^{i,j} \sqrt{\frac{c_{ij}^2}{c_i \cdot c_j}} \qquad (4)$$

$$c_{ij},\ c_{i},\ \text{and}\ c_j > 0$$

C_{ij} is the numbers of co-occurrences of i and j keywords that is equal to the number of patents having both i and j IPC classes. C_i is the numbers of occurrences of i keyword that is the number of patents having i IPC class. C_j is the numbers of occurrences of j keyword that is the number of patents having j IPC class. N is the total number of patents in a certain category of a technology. Equation (3) is a simplified form of the proximity index between two different technologies i and j. After modifying equation (3) by applying the cosine principle, we can obtain another form of simplified equation (4) where c_{ij}, c_i, and c_j are converted percentage indexes of C_{ij}, C_i, and C_j.

Since quantitative methods are likely to be too simple to measure a deep technological change by technology fusion, more concrete and comprehensive methods need to be further developed. Qualitative measures such as surveys of research papers on specific technologies, analysis of their citation patterns, and a technology analysis are alternatives. The above-mentioned two quantitative methods including analysis of research papers as a qualitative measure are empirically applied for measuring the intensity of technology fusion in the case of intelligent robots in the following section of this paper.

5. An Application to Intelligent Robots

5.1 Technology Fusion Processes of Intelligent Robots

Innovations in robot technology are likely to show distinctive characteristics of technology fusion since various professionals with different technological knowledge are involved in creating the new technologies. They cooperate in the application of vast technological knowledge such as in manufacturing, mining, electricity, medicine, social welfare, entertainment, educational, military, and many other services. As the result of this co-creation, the innovation of robots has evolved into the adoption of information, telecom, digital, and many other user technologies, which has generated into the intelligent robotics stage as shown in Figure 6.

Looking at the technological trajectories of robots, four development stages can be distinguished on technology fusion: germination stage, mobile robots stage, micro robots stage and intelligent robots stage. In the germination stage during the 1970s, simple automation machines like weavers evolved to industrial manipulators to conduct such process works as welding, punching, riveting, etc. by adopting a control mechanism and some engineering work. Also, electric motor-driven robots were introduced in many applications as electric motors were developed (Kumaresan, 2001). After new technologies such as integrating actuator, navigation, and software engineering technology were applied, sophisticated mobile robots were developed and used for assembling passenger cars and many other machineries (Baranson, 1983). This development took place in the 1980s and was called a mobile robots stage.

In the 1990s, industrial robots increasingly began to integrate new technologies such as sensing, the utilization of new materials, and micro operation. This application opened up a micro robots stage, which greatly contributed to the innovation of medical services, i.e., improving surgery and medical services. Recently, at the turn of the millennium, robots have become intelligent machines by integrating information, telecom, digital, personal computers, and various user technologies. At the same time, functions of products such as TVs, PCs, mobile phones, industrial robots, and automobiles converged into intelligent robots (MOCIE・MCI, 2005; Yuh and Negahdaripour, 1994). It has been expected that this convergence trend would generate new types of intelligent robots. For example, cleaning robots emerged in markets and have become popular for housekeepers. Developments like this fall under the intelligent robots stage.

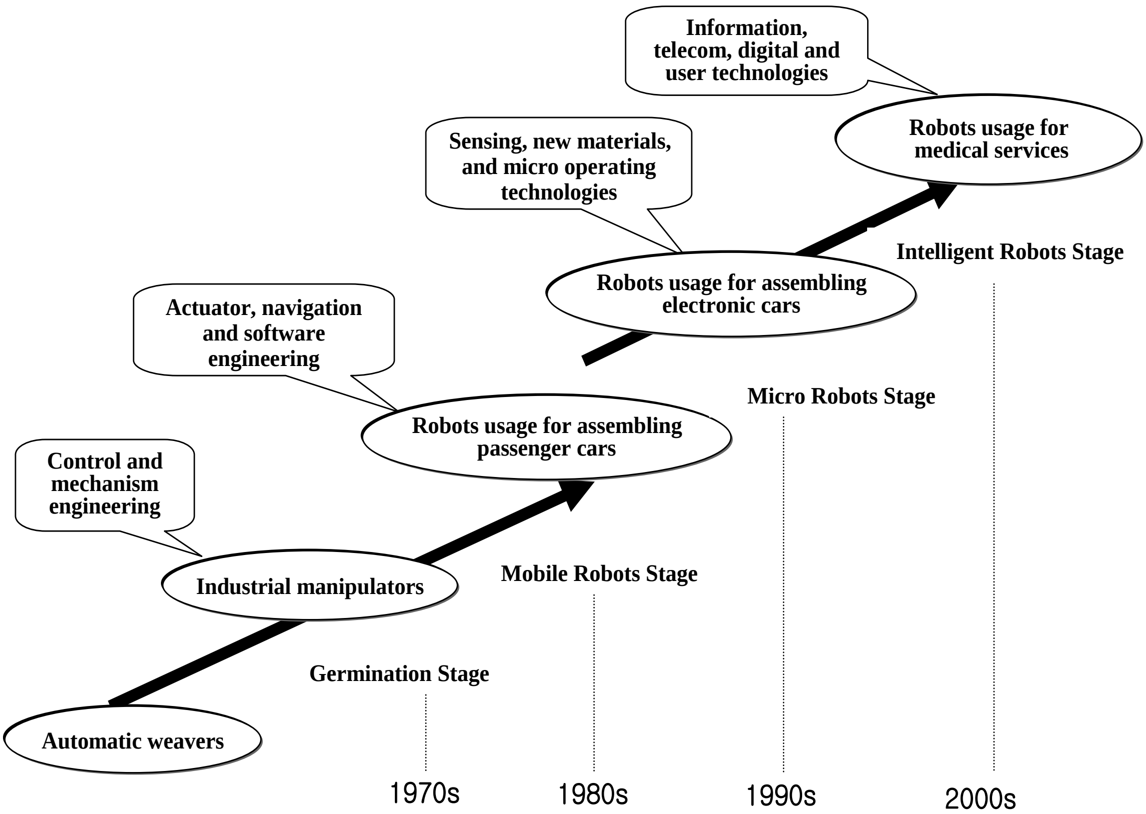


Figure 6: Technology Fusion Processes of Intelligent Robots

Intelligent robots have great market potential and possibility of technology fusion in the future, many experts argue. It is expected that intelligent robots will be widely used for carrying out various risky public services so that there will be a high social need for them to develop. Continuous innovation of intelligent robots is, therefore, feasible. At the same time, integration of various new technologies such as system, control, electronic information, view, voice and environment cognition, telecom, contents, brain science, and diverse user knowledge into intelligent robots is expected to take place in the future.

5.2 Quantitative Measure for Technology Fusion

How much degree of technology fusion has been generated in the innovation of intelligent robots? It is interesting to quantitatively see up to what extent diverse technologies integrate to create intelligent robots. Before calculating the intensity of technology fusion in intelligent robots, this paper briefly reviews the trends of innovations in intelligent robots and finds the top 10 class pairs of US patents in intelligent robots to identify major technology areas. Then, it figures out the pattern of technology fusion in intelligent robots and calculates the technological proximity that indicates technology fusion in intelligent robots based on equation (4) previously mentioned.

Analyzing the US patents of intelligent robots as for the quality of innovation during the period of 1991-2004, it can be seen that their innovative performance has been continuously increasing as revealed in Figure 7. The thin line on Figure 7 shows the trend of total number of US patent registrations, and the thick line accounts for the number of US patents with more than two technology classes that implies innovations through a technology fusion. Approximately, 60-70 percent of innovations in intelligent robots are likely to have integration of more than two technologies.

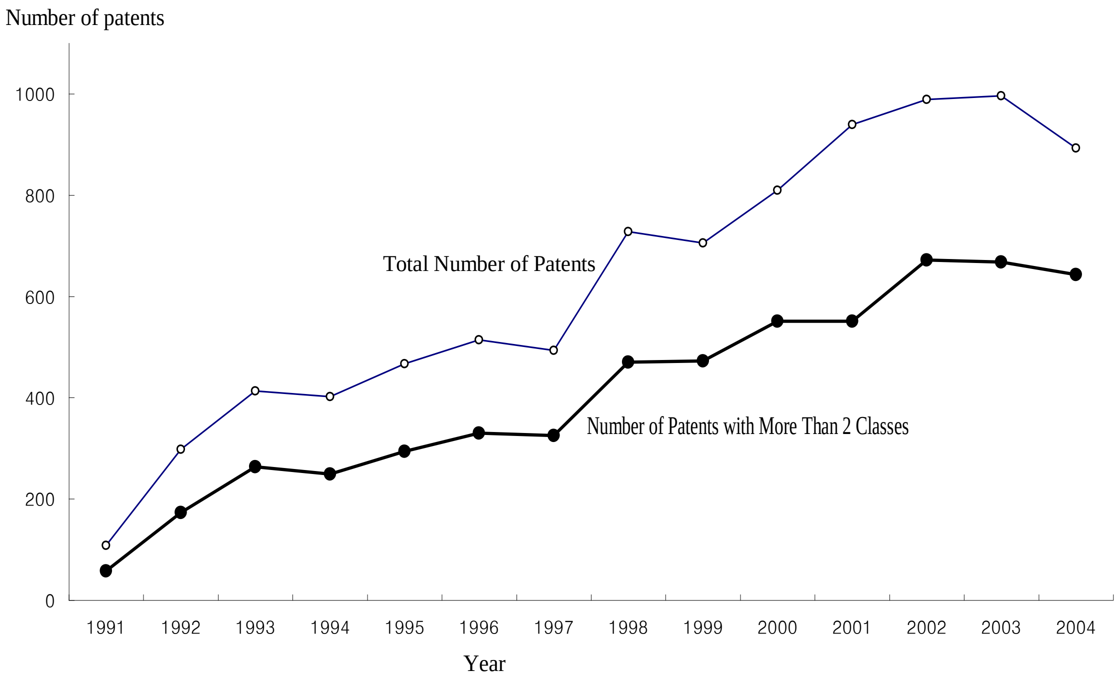


Figure 7: Trends of US Patenting in Intelligent Robots

Technology class pairs of patents that frequently appear are digital data treatment–general control (52 cases), manipulator–elevator (50 cases), general control–manipulator (43 cases), enzyme related measurement–chemical and physical analysis of materials (35 cases), digital data treatment–arithmetic logic (31 cases), crane–manipulator (31 cases), general control–manipulator (29 cases), manipulator–transport and storage tools (28 cases), toy–physical exercise tools (28 cases), and manipulator–general control (26 cases). Using equation (3), we calculated technological proximity (P) between two technologies for the 10 largest class pairs that most frequently appear as shown in Table 3. The proximity between toy and physical exercise tools turned out to be the highest (9.3333), followed by the proximity between manipulator and elevator- type robots (8.5749).

Technology proximity indexes appearing in the patents of intelligent robots well reflect the similarity of technologies making the technology class pairs. There are, however, certain limitations to say that they represent exactly the intensity of technology fusion because we emphasized the fusion of different technologies as a characteristic. Therefore, an explanation on the calculation results of technological proximity using patent data should be made with caution. We can find from the results what kinds of technologies are integrated into the inventions and innovations of intelligent robots and their relative importance.

Table 3: Top 10 Class Pairs of US Patents in Intelligent Robots

N=1,248

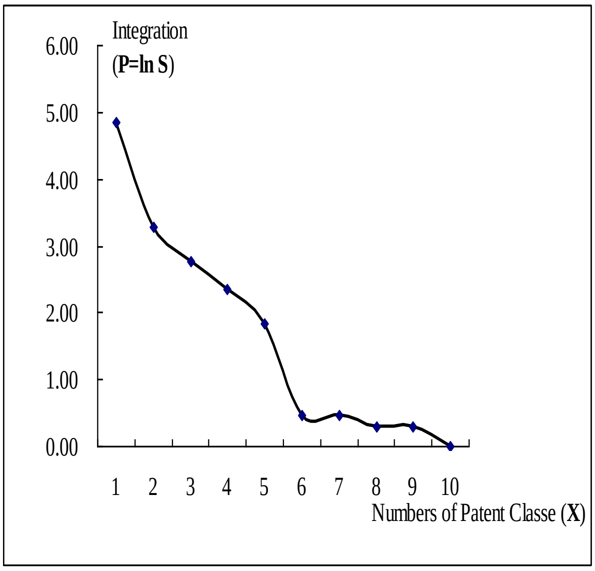
Class Pairs	Name of Technologies	Patents with the Pair (C_{ij})	Proximity (P_{ij})
G06F -	Digital data treatment – General	52	0.4308
B25J –	Manipulator – Elevator	50	8.5749
G05B -	General control – Manipulator	43	0.9365
C12Q - G01N	Enzyme related measurement - Chemical and physical analysis of materials	35	1.5590
G06F -	Digital data treatment - Arithmetic	31	0.5838
B66C –	Crane – Manipulator	31	3.7593
G05G -	General control – Manipulator	29	4.9735
B25J - B65J	Manipulator – Transport and storage	28	1.0478
A63H -	Toy - Physical exercise tools	28	9.3333
B25J –	Manipulator - General control	26	0.5663

Meanwhile, US patent statistics identify the patterns of technology fusion in intelligent robots. Analyzing the number of citations in each patent and total number of patents per the number of cited classes, a kind of technology fusion pattern of intelligent robots can be drawn as in the graph along with Table 4. The number of patents that has just one cited class indicating less possibility of technology integration appeared to be 6,390 accounting for 71.9 percent out of total number of patents. When the number of cited class increases to two, the number of patents sharply decreased to 1,701, taking 1.9 percent share out of total number of patents. Likewise, it revealed that the more the number of cited classes, the less the number of related patents found. One patent cited the largest number of technology classes; 13 indicated thirteen technologies integrated for the invention. Overall pattern of technology integration in intelligent robots is a reverse logistic curve as shown in the graph of Table 4.

What sort of insights can we obtain from this analysis and assumed patterns of technology fusion? First of all, this product-level analysis on the technology classes of patent data seems to be useful to find the scope of technological learning for interdisciplinary research teams which are to pursue projects associated with technology fusion. The more the shape of a technology fusion pattern is horizontally distributed, the stronger the interdisciplinary research team may be required to develop the product. Secondly, it may provide implications for specialized firms, especially SMEs about how to carry out innovation management such as collaboration with partners, scope of outsourcing, co-operation with suppliers, recruiting R&D manpower, etc. Lastly, comparing the pattern of technology fusion of a product with that of another product generates information about the depth and width of technology fusion of each product. It helps R&D managers estimate durations and scale of resources to develop sophisticated products with the fusion of multi-technologies.

Table 4: Pattern of Technology Fusion in Intelligent Robots

* No. of Cited class (**X**)	Total no. of patents	Share (%) (**S**)
1	6,390	71.88
2	1,701	1.91
3	523	0.59
4	207	0.23
5	58	0.07
6	3	0.003
7	3	0.003
8	2	0.002
9	2	0.002
13	1	0.001
Total	8,890	100.0



Note: * indicates that number at the four digit level.

5.3 Qualitative Investigation

Quantitative measures for technology fusion must be fascinating, but there are doubts on their accuracy, as we saw in the case of measuring the technology proximity. One complementary way is to carry out qualitative investigation together with quantitative measurement. There are probably a number of methods to qualitatively investigate the extent of technology fusion. Possible methods are qualitative investigation into the content of patents, analysis of product architecture, mapping technology trees for the product, product function-structure matrix analysis, and a literature analysis, etc. Selection of methods depends upon the characteristics of the product and the unit of analysis.

As for the case of intelligent robots, this paper chose literature analysis by using abstracts of papers presented in the IEEE/RSJ International Conference on Intelligent Robots and Systems which was held in Edmonton, AB, Canada from the second to the sixth, August 2005. In total, 624 papers associated with intelligent robots were presented in the conference. As the result of the analysis on 624 papers, 13 key words were selected: humanoid, control, service robots, sensors, systems, vision, SLAM, planning, manipulators, learning, micro/mobile, teleoperation and software. Among these keywords, the keyword “humanoid” was found to be the largest number; 86 papers used it in their titles, followed by keyword “control”, having a mention in 80 papers, and “service robots” having 76 papers mention it, as shown in Table 5.

Looking into specific phrases in papers with the keyword “humanoid”, it is found that the phrase of humanoid robots appeared in 29 papers, humanoid interaction in 24 papers, biped robots in 12 papers, face/person recognition in 5 papers, human-robot emotion in 4 papers, interaction and intelligence in 4 papers, neural fuzzy computing in 4 papers, and humanoid robot control in 4 papers. As for the keyword “control”, mobile robot control appeared in 16 papers, robot audition in 13 papers, unique robots and their control in 13 papers, redundancy control in 8 papers, pattern formation and control in 5 papers, robot hand control in 5 papers, neural controller for robots in 4 papers, control of flexible robots in 4 papers, and so on. Titles of the papers surveyed are mostly associated with basic research, not direct relationship with the product.

These results of the literature analysis provide an important implication about technology fusion in intelligent robots. Vast areas of knowledge, including humanity science have been integrated into research on intelligent robots, which obviously reveal the interdisciplinary nature of research. It implies that diverse knowledge has been fusing or integrating in the process of basic research before the commercial development of intelligent robots. It is argued in a paper that there is a wide cross-disciplinarity in knowledge sourcing for basic research works (Rafols and Meyer, 2006). Theoretical models and explanations put forward previously for the processes, mechanisms, patterns, and collective learning of technology fusion are likely to be more properly applied to the upstream of research activities or to a basic research stage than to the downstream of research activities, or developmental stage.

Table 5: Papers Presented at the International Conference on Intelligent Robots: Key Words Analysis

Key words	Key subjects of papers	Number of papers
Humanoid	Humanoid robots (29), humanoid interaction (24), biped robots (12), face/person recognition (5), human-robot emotion (4), interaction and intelligence (4), neural fuzzy computing (4), humanoid robot control (4)	86
Control	Mobile robot control (16), robot audition (13), unique robots and their control (13), redundancy control (8), pattern formation and control (5), robot hand control (5), neural controller for robots (4), control of flexible robots (4), sliding mode control (4), multi-	80

	robot control (4)	
Service Robots	Surgical robots (13), unmanned aerial robots (13), underwater robots (8), snake robots (8), biomedical robots and applications (5), planetary rovers (5), personal robots (4), welfare robots (4), wheelchair robots (4), socially friendly robots (4), demining robots (4), other service robots (4),	76
Sensors	Sensors network (24), haptic display (10), micro/nano sensing and manipulation (5), object recognition (5), multi-modal sensing (4), tactile sensing (4), range sensing (4), force/torque sensing (4), vision sensors (4), cooperative sensing (3), sensors for robot localization (3)	70
Systems	Multi-robot systems (34), actuators (10), exoskeletons (9), manufacturing automation (5), biomimetric robots and systems (4)	62
Vision	Visual servo (15), vision and applications (8), stereo vision (5), vision calibration (5), vision architecture (5), vision and motion (5), vision for reconstruction and monitoring (4), vision and environment structure (4), vision and planning (4), real-time vision (3)	58
SLAM	Vision based SLAM (14), algorithms (10), features and bias issues (4), loop closing (4), data association (4), range sensing based SLAM (4), 3D SLAM (4), map building (4), bearing only SLAM (4)	52
Planning	Motion planning (13), path planning (10), task planning (5), shape/profile measurement (4), probabilistic methods in robotics (4), grasp planning and optimization (4), incremental mapping (4)	44
Manipulators	Parallel manipulator analysis (14), micro/nano manipulation (5), grasp analysis (5), under-actuated manipulation (4), manipulator motion planning (4), multi-fingered manipulation (4)	36
Learning	Robot learning (13), contact dynamics (8), behavior learning (4), learning by interaction (4), learning for robot control (4)	33
Micro/Mobile	Mobile robot localization (14), micro mobile robots (5), bio-application for micro robots (4), mobile robot scheduling and coverage (3)	27
Teleoperation	Teleoperation (10), telemanipulation (4), time-delay in teleoperation (4), new concepts and techniques in teleoperation (4)	22
Software	Robot software and programming	14
Total	92 subjects	624

Note: SLAM is the abbreviation of simultaneous localization and mapping. It is a technique used by robots and autonomous vehicles to build up a map within an unknown environment while at the same time keeping track of their current position.

Source: IEEE (2005), *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems,* Edmonton, AB, Canada, 2-6 August, Vol. 1-4.

5. Concluding Remarks

The concept of Bell's learning process and technological capability is usefully applied to this understanding of technology fusion involving a complex learning process. Technology fusion is simply defined as horizontal integration of diverse technologies. The result of technology fusion may appear in two types. One is a convergence type, in which a critical technology tends to converge into many different technologies. The other type is a fractal type, in which two different technologies fuse and create a completely different type of technology. Both types of technology fusion require interdisciplinary research teams composed of many professionals with different technological knowledge, in which they interact and create new ideas and knowledge.

The learning mechanisms for technology fusion typically begin as the researcher with a cognitive map on one technology interacts with another researcher holding different cognitive maps. Their interaction evolves into a collective learning that causes to generate a new knowledge. The collective knowledge also creates a new technology after it integrates into or absorbs a codified and tacit knowledge created by the third researcher with other knowledge. Under active social interaction and learning among many research professionals, the diversity of application for a given technology is quite large so that the possibility of technology fusion to create new functions and products becomes available.

To measure a technological change by technology fusion is an interesting issue. The estimation of an exponential function of number of different technologies or cumulative proximity between different technologies may be a possible method to quantitatively measure technology fusion. They are, however, likely to be too simple to estimate sophisticated fusion of technologies so that certain a qualitative method is required as a complementary for quantitative measures. Whatever the method is, estimation results of technology fusion may be useful to find the scope of technological learning for interdisciplinary research teams and direction of innovation management, for instance, providing an important input into durations and scale of resources to develop sophisticated products with the fusion of multi-technologies. As Bell would insists, in-depth case data is required to reveal the changing dynamics of technology fusion.

In the case investigation of intelligent robots, technology fusion appears to be quite distinctive in which core technologies such as digital data treatment, control or adjustment, and manipulator are the leading components in the integration of various technologies of intelligent robots. The literature analysis using abstracts of 624 papers on intelligent robots provided such key words as humanoid, control, service robots, sensors, systems, vision, manipulators, learning, micro/mobile, teleoperation, software, etc. It was found that vast areas of knowledge, including humanity science have been integrated into the research on intelligent robots, implying that diverse knowledge has been fusing or integrating in the process of basic research before the commercial development of intelligent robots.

References

Baranson, J. (1983), *Robots in Manufacturing, Key to International Competitiveness*, Maryland: Lomond Publications, Inc.

Bell, Martin (1984), "Learning' and the Accumulation of Industrial Technological Capacity in Developing Countries" in M. Fransman, & K. King (eds.), *Technological Capability in the Third World*, pp. 187-209. London: Macmillan.

Bell, M. and Pavitt, K. (1995), "The Development of Technological Capabilities", in Irfan-ul-Hague (ed.), *Trade, Technology and Industrial Competitiveness*, pp. 69-101. Washington: World Bank.

Fujimoto, T. (2007), "Architecture-based Competitive Advantage – A Design Information View of Manufacturing", *Evolutionary and Institutional Economics Review*, Vol. 4, No. 1, pp. 55-112, Tokyo: Japan Association for Evolutionary Economics.

Grupp, H. (1994), "The Dynamics of Science-Based Innovation Reconsidered: Cognitive Models of Statistical Findings", in Granstrand, O. (ed.), *Economics of Technology*, Amsterdam: Elsevier Science.

Hwang, Jung-Tae (2005) "Does Technology Fusion Generates Technological Opportunities?", Paper presented for *STEPI International Symposium*, Seoul: STEPI.

Hwang, Jung-Tae and Kim, Byung-Keun (2006), "Analysis on the Multi-technology Capabilities of Korea and Taiwan Using Patent Bibliometrics", *Asian Journal of Technology Innovation*, Vol. 14, No. 2, pp. 183-199.

Hwang, Jung-Tae (2006), *The Role of Small Innovative Firms in Multi-technology Innovation: The Case of Rapid Prototyping Industry*, D.Phil Dissertation, Brighton: University of Sussex.

Iansiti, M. (1998), *Technology Integration*, Boston: Harvard Business School Press.

IEEE (2005), *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Edmonton, AB, Canada, 2-6 August, Vol. 1-4.

International Federation of Robotics (2004), *World Robotic.*

Kodama, F. (1994), *Emerging Patterns of Innovation*, Boston: Harvard University Press.

Kodama, F. (1991), *Analyzing Japanese High Technologies: The Techno Paradigm Shift*, London: Pinter Publishers.

Kodama, F. (1986), "Inter-disciplinary Research: Japanese Innovation in Mechatronics Technology", *Science and Public Policy*, Vol. 13, No.1, pp. 44-51.

Kumaresan, N. (2001), *Dynamics of Technology Accumulation and Evolution of Distributed Industries: The Case of Robotics Industry*, Ph.D. Thesis, Tokyo: Tokyo Institute of Technology.

Chung, KunMo and Lee, Kong-rae (1999), "Mid-entry Technology Strategy: The Korean Experience with CDMA", *R&D Management*, Vol. 29, No. 4, pp. 353-363.

Lee, Kong-rae and Hwang, Jung-tae (2005), *A Study on Innovation System with Multi-technology Fusion* (in Korean), Seoul: STEPI Policy Study 2005-17.

Lim, Woo-Suk (2004), "Digital, Digerati, and Digital Convergence", *Science Culture*, (in Korean), No. 53, pp. 6-7, Seoul: Korea Science Foundation.

Miller, W. L. and Morris, L. (1999), *4th Generation R&D -Managing Knowledge, Technology and Innovation*, New York: John Wiley & Sons, Inc.

MOCIE · MIC (2005), *Visions and Development Strategy of the Intelligent Robots Industry* (in Korean), Seoul: Ministry of Commerce, Industry and Energy (MOCIE) and Ministry of Information and Communication (MIC).

Nonaka, I. (1994), "A Dynamic Theory of Organizational Knowledge Creation", *Organizational Science*, Vol. 5, No. 1, pp. 14-37.

OECD (1993), *Technology Fusion: A Path to Innovation, The Case of Optoelectronics*, Paris: OECD.

Rafols, I. and Meyer, M. (2006), *Knowledge-sourcing Strategies for Cross-disciplinarity in Bionanotechnology*, Brighton: SPRU Electronic Working Paper Series: 152.

Roco, M. C. and Bainbridge, W. S. (2002), *Converging Technologies for Improving Human Performance*, Arlington, Virginia: NSF.

Rosenberg, N. (1982), *Inside the Black Box -Technology and Economics*, Cambridge: Cambridge University Press.

Rosenberg, N. (1963), "Technological Change in the Machine Tool Industry, 1840-1910", *Journal of Economic History*, Vol. 23, No. 4, pp. 414-446.

Seok-Ji, Park (2004), "A Prospective on the Evolution of Mobile Communications in Korea", Paper presented to the *PICMET-STEPI International Conference on Innovation Management in the Technology-Driven World*, 31 July-2 August, Seoul.

Teece, D. J. (1976), *Vertical Integration and Vertical Divestiture in the US Petroleum Industry*, Stanford Institute for Energy Studies.

Tidd, J., Bessant, J. and Pavitt, K. (2001), *Managing Innovation*, Chichester: John Wiley& Sons.

Yuh, J. and Negahdaripour, S. (1994), *Report of the Workshop on Future Research Directions in Underwater Robotics*, Washington D. C.: National Science Foundation.